Reprinted from the preprint volume of the **21ST CONFERENCE ON HURRICANES AND TROPICAL METEOROLOGY**, April 24-28, 1995, Miami, FL by the American Meteorological Society, Boston, MA.

15B.1

NUMERICAL STUDY OF THE ASYMMETRIC STRUCTURE IN THE INTERIOR OF TROPICAL CYCLONES

Morris A. Bender

Geophysical Fluid Dynamics Laboratory
Princeton University, P.O. Box 308
Princeton, NJ, 08542-0308

1. INTRODUCTION

The topic of asymmetry in the structure of tropical cyclones, has received increased attention in recent years both through observational and theoretical studies. Many observational studies have confirmed that the hurricane circulation and the organization of convection in the interior core of tropical cyclones often possess a highly asymmetric structure. Likewise, through numerical and analytic studies, it has become well established that an initially symmetric vortex will develop an asymmetric structure (commonly referred to as a beta-gyre) due to interaction of the vortex with the earth's vorticity gradient. However, most of the previous studies of tropical cyclone asymmetry induced by the beta effect have not addressed the possible effect of the beta-gyre on the storm's interior structure, particularly processes such as precipitation since investigation of this problem requires the use of a high resolution model.

The purpose of this study is to investigate the possible role of the beta effect on the generation of asymmetries in the distribution of precipitation, convergence and upward motion in the interior region of tropical cyclones based on numerical results from the GFDL high-resolution tropical cyclone model. The asymmetries introduced by the addition of a simple basic flow as well as the modification of the asymmetries by introduction of the ocean-interaction will also be investigated.

2. EXPERIMENTAL DESIGN

A set of idealized numerical experiments was performed with an experiment run with no initial basic flow, constant 302 K sea surface temperature (SST) and variable Coriolis parameter (f) with latitude designated as the control experiment. Subsequent experiments were then performed with constant f, the addition of a 5 m s^{-1} easterly basic flow (constant with height), or with the inclusion of hurricane-ocean coupling in order to assess the impact of these effects on the generated asymmetric structure of the model storm. One final supplemental experiment was also run with a vertically sheared basic flow which initially increased from 5 m s^{-1} above the boundary layer to a value of 16 m s^{-1}, at 10 km.

The outer domain of the model ranged from the equator to 55°N while the inner mesh with 1/6° resolution moved with the storm center. For each of the experiments the profile of the tangential wind for Hurricane Gloria at 1200 UTC 22 September, 1985 (just after the storm was first upgraded to a hurricane) was used as the initial condition of the hurricane. Following the procedure outlined in Bender et al., 1993, the obtained symmetric vortex was placed onto the environmental fields at 18°N, with each experiment integrated to 72h.

3. RESULTS

The results presented were time averaged for the entire period of integration and computed relative to the moving storm. This approach was used to emphasize the quasi-steady component of precipitation, convergence and upward motion, which tend to be dominated at any instant by high-frequency fluctuations. In the control experiment the tropical cyclone reached a maximum intensity of about 938 hPa. When the azimuthally averaged tangential profile was subtracted from the total wind field the relative vorticity of the resulting asymmetric flow exhibited a wave number 1 dipolar structure (i.e., the beta-gyre) with a vorticity minimum (maximum) located 450 km north-northeast (south-southwest) of the storm center.

The direction of the asymmetric flow field was oriented in a north-northwest direction, in good agreement with the storm motion. As seen in Fig. 1, the asym-

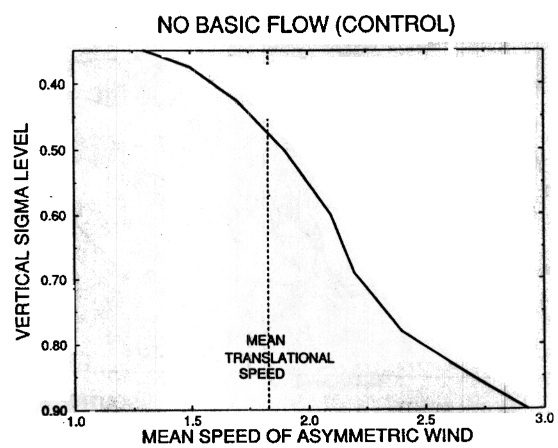

Fig. 1 Distribution of the mean asymmetric wind speed (m s^{-1}) as a function of height computed from the wind field averaged for the entire 72h integration. The storm's mean translational speed is shown by a dashed line.

metric wind speed in the lower part of the free atmosphere exceeded the storm's translational speed by slightly more than 1 m s^{-1}, resulting in cross flow into the eyewall. Although the instantaneous distribution of divergence in the lower free atmosphere was characterized by bands of convergence and divergence that tended to propagate outward from the storm center, a persistent area of weak divergence existed in the 72h time-averaged wind field ahead of the propagating storm with enhanced convergence in the rear eyewall (Fig. 2). Apparently, as the asymmetric flow approached the high relative vorticity region of the eyewall it tended to conserve potential vorticity, undergoing stretching and then shrinking as it exited on the other side. The average static stability in the lower free atmosphere was about 7% larger in the northwest eyewall compared to the eye, hinting that shrinking was occurring there.

As seen in Fig. 2, this resulted in asymmetries

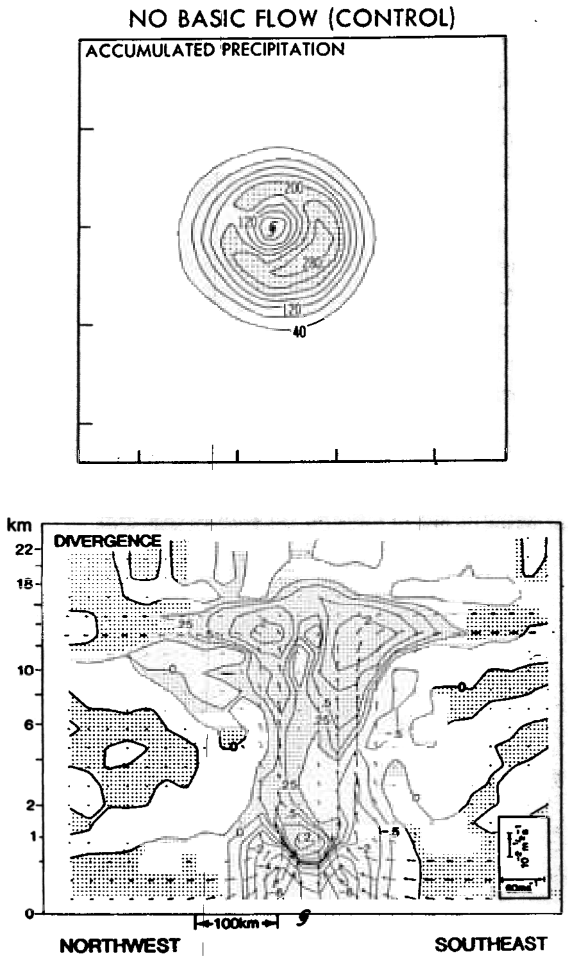

Fig. 2 Distribution of the 72h accumulated precipitation (cm) relative to the storm (top) and northwest-southeast cross-section through the storm center of the flow field and divergence (10^{-4} s^{-1}; shading positive) averaged for the entire 72h of the integration.

in the accumulated precipitation (top) and the time averaged field of omega (bottom), with stronger upward motion on the southeast side of the eyewall throughout much of the troposphere. Within the eyewall, the accumulated precipitation ranged from 180 cm on the northwest side to over 280 cm southeast of the storm center. The strongly asymmetric structure in the storm precipitation was usually not apparent in the distribution of the instantaneous precipitation fields since the strong convective cells, which rotated cyclonically around the storm, were located in each quadrant at various periods during the integration. However, the most intense convective activity was found in the southeast sector of the storm 37% of the time (compared to 8% in the northwest side), as this quadrant became a favored region for the intensification of the convective cells which often underwent weakening in the region northwest of the eye. In the experiment with constant f, the accumulated precipitation distribution was nearly symmetric.

In the next experiment a 5 m s^{-1} easterly flow was added to the control to evaluate the effect of the basic flow on the vortex. The average boundary layer convergence (Fig. 3) was significantly altered with maximum convergence shifted to ahead and just to the right of the storm, associated with the region of maximum inflow. Despite the concentration of boundary layer convergence ahead of the translating vortex, the asymmetry in the precipitation distribution remained similar to the control case as the maximum accumulated precipitation remained in the southeast sector of the storm. Analysis indicated that in the lower part of the free atmosphere (2-4 km height), the interaction of the basic flow with the vortex also produced a divergent region ahead of the storm and convergence behind the storm center in the eyewall region. Because of the effect of this compensat-

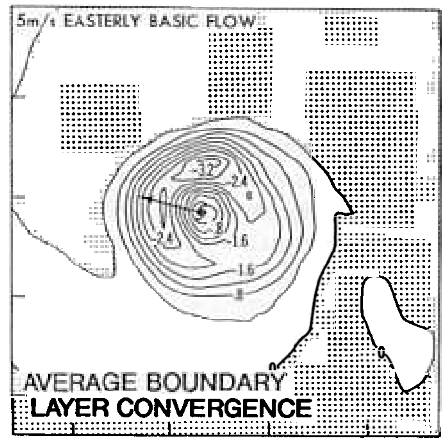

Fig. 3 Averaged boundary layer convergence (10^{-4} sec $^{-1}$) for the experiment with a 5 m s^{-1} easterly basic flow averaged for the entire 72h integration and computed relative to the moving storm. Positive values shaded.

ing divergence (convergence) in the free atmosphere ahead of (behind) the storm, the basic flow did not significantly impact the storm's precipitation distribution.

Observations have shown that the front sector of propagating tropical cyclones is often found to be a favored region of maximum rainfall. This suggests that other mechanisms possibly associated with the vertical and horizontal variations of the environmental wind may play a major role in modifying the type of asymmetric structure presented here. In order to access the impact of vertical wind shear, another experiment was performed in which the initial easterly basic flow was increased above the boundary layer as shown in Fig. 4. Since the storm moved about 4-5 m s^{-1} faster than the mean boundary layer zonal component of the winds, the winds relative to the moving storm were from the front in the lower levels. The asymmetry in the boundary layer convergence (Fig. 4, bottom) was significantly increased compared to the case with the 5 m s^{-1} constant easterly basic flow as greater boundary layer convergence occurred ahead of the storm center with decreased convergence to the rear. As a result the precipitation maximum shifted to the front left quadrant of the storm (Fig. 4, top). This suggests that the observed bias of maximum precipitation toward the front quadrant of propagating tropical cyclones may be related to vertical changes in the environmental winds among other factors as well. Nevertheless, the mechanism that generated the asymmetric precipitation pattern in the control case, is likely one of the many factors that can contribute to storm asymmetry and may become important when the environmental flow is weak.

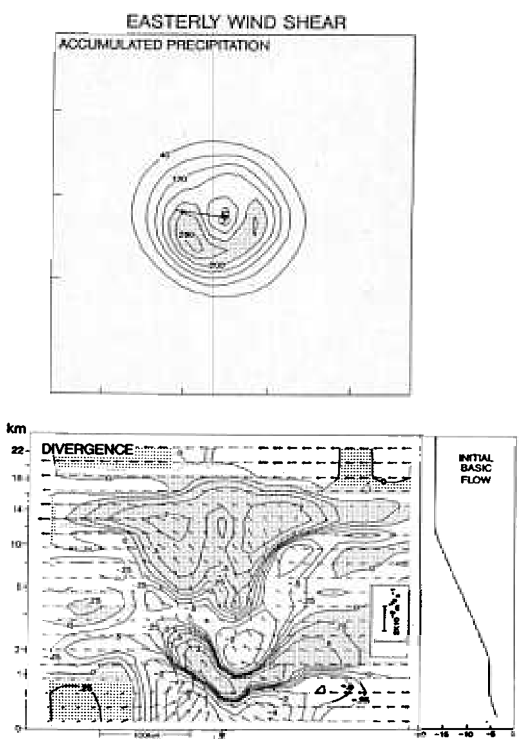

Fig. 4 Distribution of accumulated precipitation and west-east cross-section through the storm center of the flow field and the divergence for the easterly shear case. The vertical profile of the initial basic flow is shown.

In a final experiment the control experiment was modified by coupling the hurricane model with the high-resolution ocean model described by Bender et al., 1993. This produced a region of lower SST behind the storm. Since the storm in this experiment averaged 16 hPa weaker than in the control, the precipitation and omega decreased in all four quadrants. In addition, difference maps between the coupled and non-coupled experiment indicated that the air over the cold wake became more divergent throughout most of the troposphere (Fig. 5), with the maximum decrease in upward motion clearly biased toward the southeast side of the storm. Hence, the decrease in precipitation was greatest over the cold wake (i.e., over 120 cm), shifting the location of maximum rainfall to the eastern side of the eyewall. These results suggest that the tropical cyclone-ocean interaction may be an additional mechanism that can modify the asymmetric distribution of the hurricane's precipitation, upward motion and convergence.

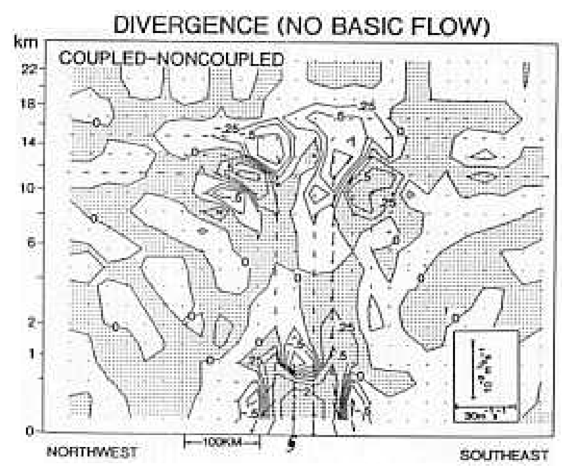

Fig. 5 Northwest-southeast cross-section through the storm center of the difference in the flow field and the divergence between the coupled and non-coupled experiments, computed from the 72h averaged fields.

4. REFERENCES

Bender, M.A., I. Ginis, and Y. Kurihara, 1993: Numerical simulations of tropical cyclone-ocean interaction with a high resolution coupled model. *J. Geophs. Res.*, **98**, 23245-23263.